Modulation

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For other uses, see Modulation (disambiguation).

Modulation techniques
Analog modulation
AM · SSB · FM · PM · SM
Digital modulation
OOK · FSK · ASK · PSK · QAM
MSK · CPM · PPM · TCM · OFDM
Spread spectrum
FHSS · DSSS
See also: Demodulation

In telecommunications, modulation is the process of varying a periodic waveform, i.e. a tone, in order to use that signal to convey a message, in a similar fashion as a musician may modulate the tone from a musical instrument by varying its volume, timing and pitch. Normally a high-frequency sinusoid waveform is used as carrier signal. The three key parameters of a sine wave are its amplitude ("volume"), its phase ("timing") and its frequency ("pitch"), all of which can be modified in accordance with a low frequency information signal to obtain the modulated signal.

A device that performs modulation is known as a modulator and a device that performs the inverse operation of modulation is known as a demodulator (sometimes detector or demod). A device that can do both operations is a modem (short for "MOdulate-DEModulate").

> A simple example: A telephone line is designed for transferring audible sounds, for example tones, and not digital bits (zeros and ones). Computers may however communicate over a telephone line by means of modems, which are representing the digital bits by tones, called symbols. You can say that modems play music for each other. If there are four alternative symbols (corresponding to a musical instrument that can generate four different tones, one at a time), the first symbol may represent the bit sequence 00, the second 01, the third 10 and the fourth 11. If the modem plays a melody consisting of 1000 tones per second, the symbol rate is 1000 symbols/second, or baud. Since each tone represents a message consisting of two digital bits in this example, the bit rate is twice the symbol rate, i.e. 2000 bit per second.

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The aim of modulation

The aim of digital modulation is to transfer a digital bit stream over an analog bandpass channel, for example over the public switched telephone network (where a filter limits the frequency range to between 300 and 3400 Hz) or a limited radio frequency band.

The aim of analog modulation is to transfer an analog lowpass signal, for example an audio signal or TV signal, over an analog bandpass channel, for example a limited radio frequency band or a cable TV network channel.

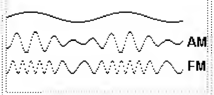
Analog and digital modulation facilitate frequency division multiplexing (FDM), where several low pass information signals are transferred simultaneously over the same shared physical medium, using separate bandpass channels.

The aim of digital baseband modulation methods, also known as line coding, is to transfer a digital bit stream over a lowpass channel, typically a non-filtered copper wire such as a serial bus or a wired local area network.

The aim of pulse modulation methods is to transfer a narrowband analog signal, for example a phone call over a wideband lowpass channel or, in some of the schemes, as a bit stream over another digital transmission system.

Analog modulation methods

In analog modulation, the modulation is applied continuously in response to the analog information signal.



A low-frequency message signal (top) may be carried by an AM or FM radio wave.

Common analog modulation techniques are:

- Amplitude modulation (AM) (here the amplitude of the modulated signal is varied)
    - Double-sideband modulation DSB
        - Double-sideband modulation with unsuppressed carrier (DSB-WC) (used on the AM radio broadcasting band)
        - Double-sideband suppressed-carrier transmission (DSB-SC)
        - Double-sideband reduced carrier transmission (DSB-RC)
    - Single-sideband modulation (SSB, or SSB-AM),
        - SSB with carrier (SSB-WC)
        - SSB suppressed carrier modulation (SSB-SC)
    - Vestigial sideband modulation (VSB, or VSB-AM)
    - Quadrature amplitude modulation (QAM)

- Angle modulation
    - Frequency modulation (FM) (here the frequency of the modulated signal is varied)
    - Phase modulation (PM) (here the phase shift of the modulated signal is varied)

Digital modulation methods

In digital modulation, an analog carrier signal is modulated by a digital bit stream. Digital modulation methods can be considered as digital-to-analog conversion, and the corresponding demodulation or detection as analog-to-digital conversion. The changes in the carrier signal are chosen from a finite number of M alternative symbols (the modulation alphabet).

Fundamental digital modulation methods

These are the most fundamental digital modulation techniques:

- In the case of PSK, a finite number of phases are used.
- In the case of FSK, a finite number of frequencies are used.
- In the case of ASK, a finite number of amplitudes are used.
- In the case of QAM, a finite number of at least two phases, and at least two amplitudes are used.

In QAM, an inphase signal (the I signal, for example a cosine waveform) and a quadrature phase signal (the Q signal, for example a sine wave) are amplitude modulated with a finite number of amplitudes, and summed. It can be seen as a two-channel system, each channel using ASK. The resulting signal is equivalent to a combination of PSK and ASK.

In all of the above methods, each of these phases, frequencies or amplitudes are assigned a unique pattern of binary bits. Usually, each phase, frequency or amplitude encodes an equal number of bits. This number of bits comprises the *symbol* that is represented by the particular phase.

If the alphabet consists of $M = 2^N$ alternative symbols, each symbol represents a message consisting of N bits. If the symbol rate (also known as the baud rate) is f_S symbols/second (or baud), the data rate is Nf_S bit/second.

For example, with an alphabet consisting of 16 alternative symbols, each symbol represents 4 bits. Thus, the data rate is four times the baud rate.

In the case of PSK, ASK or QAM, where the carrier frequency of the modulated signal is constant, the modulation alphabet is often conveniently represented on a constellation diagram, showing the amplitude of the I signal at the x-axis, and the amplitude of the Q signal at the y-axis, for each symbol.

Modulator and detector principles of operation

PSK and ASK, and sometimes also FSK, are often generated and detected using the principle of QAM. The I and Q signals can be combined into a complex-valued signal $I+jQ$ (where j is the imaginary unit). The resulting so called equivalent lowpass signal or equivalent baseband signal is a representation of the real-valued modulated physical signal (the so called passband signal or RF signal).

These are the general steps used by the modulator to transmit data:

1. Group the incoming data bits into codewords, one for each symbol that will be transmitted.
2. Map the codewords to attributes, for example amplitudes of the I and Q signals (the equivalent

low pass signal), or frequency or phase values.

3. Adapt pulse shaping or some other filtering to limit the bandwidth and form the spectrum of the equivalent low pass signal, typically using digital signal processing.
4. Perform digital-to-analog conversion (DAC) of the I and Q signals (since today all of the above is normally achieved using digital signal processing, DSP).
5. Generate a high-frequency sine wave carrier waveform, and perhaps also a cosine quadrature component. Carry out the modulation, for example by multiplying the sine and cosine wave form with the I and Q signals, resulting in that the equivalent low pass signal is frequency shifted into a modulated passband signal or RF signal. Sometimes this is achieved using DSP technology, for example direct digital synthesis using a waveform table, instead of analog signal processing. In that case the above DAC step should be done after this step.
6. Amplification and analog bandpass filtering to avoid harmonic distortion and periodic spectrum

At the receiver side, the demodulator typically performs:

1. Bandpass filtering.
2. Automatic gain control, AGC (to compensate for attenuation, for example fading).
3. Frequency shifting of the RF signal to the equivalent baseband I and Q signals, or to an intermediate frequency (IF) signal, by multiplying the RF signal with a local oscillator sinewave and cosine wave frequency (see the superheterodyne receiver principle).
4. Sampling and analog-to-digital conversion (ADC) (Sometimes before or instead of the above point, for example by means of undersampling).
5. Equalization filtering, for example a matched filter, compensation for multipath propagation, time spreading, phase distortion and frequency selective fading, to avoid intersymbol interference and symbol distortion.
6. Detection of the amplitudes of the I and Q signals, or the frequency or phase of the IF signal.
7. Quantization of the amplitudes, frequencies or phases to the nearest allowed symbol values.
8. Mapping of the quantized amplitudes, frequencies or phases to codewords (bit groups);.
9. Parallel-to-serial conversion of the codewords into a bit stream.
10. Pass the resultant bit stream on for further processing such as removal of any error-correcting codes.

As is common to all digital communication systems, the design of both the modulator and demodulator must be done simultaneously. Digital modulation schemes are possible because the transmitter-receiver pair have prior knowledge of how data is encoded and represented in the communications system. In all digital communication systems, both the modulator at the transmitter and the demodulator at the receiver are structured so that they perform inverse operations.

Non-coherent modulation methods do not require a receiver reference clock signal that is phase synchronized with the sender carrier wave. In this case, modulation symbols (rather than bits, characters, or data packets) are asynchronously transferred. The opposite is coherent modulation.

List of common digital modulation techniques

The most common digital modulation techniques are:

- Phase-shift keying (PSK):
  - Binary PSK (BPSK), using M=2 symbols
  - Quadrature (QPSK), using M=4 symbols

- 8PSK, using M=8 symbols
- 16PSK, usign M=16 symbols
- Differential PSK (DPSK)
- Differential QPSK (DQPSK)
- Offset QPSK (OQPSK)
- π/4–QPSK

- Frequency-shift keying (FSK):
  - Audio frequency-shift keying (AFSK)
  - Multi-frequency shift keying (M-ary FSK or MFSK)
  - Dual-tone multi-frequency (DTMF)
  - Continuous-phase frequency-shift keying (CPFSK)
- Amplitude-shift keying (ASK):
  - On-off keying (OOK), the most common ASK form
  - M-ary vestigial sideband modulation, for example 8VSB
- Quadrature amplitude modulation (QAM) - a combination of PSK and ASK:
  - Polar modulation like QAM a combination of PSK and ASK.
- Continuous phase modulation (CPM) methods:
  - Minimum-shift keying (MSK)
  - Gaussian minimum-shift keying (GMSK)
- Orthogonal frequency division multiplexing (OFDM) modulation:
  - discrete multitone (DMT) - including adaptive modulation and bit-loading.
- Wavelet modulation
- Trellis coded modulation (TCM), also known as trellis modulation

See also spread spectrum and digital pulse modulation methods.

MSK and GMSK are particular cases of continuous phase modulation (CPM). Indeed, MSK is a particular case of the sub-family of CPM known as continuous-phase frequency-shift keying (CPFSK) which is defined by a rectangular frequency pulse (i.e. a linearly increasing phase pulse) of one symbol-time duration (total response signaling).

OFDM is based on the idea of frequency division multiplexing (FDM), but is utilized as a digital modulation scheme. The bit stream is split into several parallel data streams, each transferred over its own sub-carrier using some conventional digital modulation scheme. The modulated sub-carriers are summed to form an OFDM signal. OFDM is considered as a modulation technique rather than a multiplex technique, since it transfers one bit stream over one communication channel using one sequence of so-called OFDM symbols. OFDM can be extended to multi-user channel access method in the Orthogonal Frequency Division Multiple Access (OFDMA) and MC-OFDM schemes, allowing several users to share the same physical medium by giving different sub-carriers or spreading codes to different users.

Of the two kinds of RF power amplifier, switching amplifiers (Class C amplifiers)cost less and use less battery power than linear amplifiers of the same output power. However, they only work with relatively constant-amplitude-modulation signals such as angle modulation (FSK or PSK) and CDMA, but not with QAM and OFDM. Nevertheless, even though switching amplifiers are completely unsuitable for normal QAM constellations, often the QAM modulation principle are used to drive switching amplifiers with these FM and other waveforms, and sometimes QAM demodulators are used to receive the signals put out by these switching amplifiers.

Digital baseband modulation or line coding

The term digital baseband modulation is synonymous to line codes, which are methods to transfer a digital bit stream over an analog lowpass channel using a pulse train, i.e. a discrete number of signal levels, by directly modulating the voltage or current on a cable. Common examples are unipolar, non-return-to-zero (NRZ), Manchester and alternate mark inversion (AMI) coding.

Pulse modulation methods

Pulse modulation schemes aim at transferring a narrowband analog signal over an analog lowpass channel as a two-level quantized signal, by modulating a pulse train. Some pulse modulation schemes also allow the narrowband analog signal to be transferred as a digital signal (i.e. as a quantized discrete-time signal) with a fixed bit rate, which can be transferred over an underlying digital transmission system, for example some line code. They are not modulation schemes in the conventional sense since they are not channel coding schemes, but should be considered as source coding schemes, and in some cases analog-to-digital conversion techniques.

- Pulse-code modulation (PCM) (Analog-over-digital)
- Pulse-width modulation (PWM) (Analog-over-analog)
- Pulse-amplitude modulation (PAM) (Analog-over-analog)
- Pulse-position modulation (PPM) (Analog-over-analog)
- Pulse-density modulation (PDM) (Analog-over-digital)
- Sigma-delta modulation ($\Sigma\Delta$) (Analog-over-digital)
- Continuously variable slope delta modulation (CVSDM), also called Adaptive-delta modulation (ADM)(Analog-over-digital)

Direct-sequence spread spectrum (DSSS) is based on pulse-amplitude modulation.

Miscellaneous modulation techniques

- The use of on-off keying to transmit Morse code at radio frequencies is known as continuous wave (CW) operation.
- Adaptive modulation
- Space modulation A method whereby signals are modulated within airspace, such as that used in Instrument landing systems.

See also

- Demodulation
- Electrical resonance
- Modulation order
- Types of radio emissions
- Communications channel
- Channel access methods
- Channel coding
- Line code
- Telecommunication

- Modem
- RF modulator
- Codec
- Ring modulation

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IEEE STD	IEEE Standard

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1. Pulse Shaping Filter Design and Interference Analysis in UWB Comr
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...medium ranges. Due to its wide bandwidth, UWB has a capabil
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2. Efficient bit interleaver for a multi-band OFDM ultra-wideband syst
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2007
patno:US7313190
...the various tone and sub-bands...encoded bits of a multi-band
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...less) of the UWB tones, which...and the bit rate increases...avai
tone decreases...to form a multi-tone communications...multiton
second bit stream 140...embodiments, a multi-tone communicati
of about...360, the UWB system illustrated...include a multi- bit e
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...methods employing ultra wide bandwidth (UWB) signaling tech art meaning that the signal bandwidth is equal to 25% or more of the present invention relates to UWB communication transceivers, that is a narrowband tone, which can be isolated with a narrow...s video and multi-media in the context of multi-user networked...
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MCCORKLE, John W. (XTREMESPECTRUM, INC.), *PATENT COC APPLICATION*, Dec 2001
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...embodiments of the present invention produce UWB waveforms modulated...quadrature phase signals (+1, -1, +j, J), (iv) multi-pl j7c/N), exp...N), exp(- j7r(N-l)/N)), (v) multilevel multi-phase sig f...combination of the above waveforms, such as multi-phase char according...
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144. Adaptive arrays and diversity antenna configurations for handheld terminals
Dietrich, Carl B. , Jan 2000
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...such as power consumption optimization, multi- standard comp
capability and wide signal bandwidth capacity, are often encounte
Ratio (SNR) at 0.1% Bit Error Rate (BER) is achieved with less...is
quired multi-standard compatibility. An online digital...ADI design
(UWB) receiver is also studied at system...proposed to satisfy the
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...constant pricing coe□cient with the units of bit/J, γi denotes the
γi...di□erent for compensation. Basically, DS UWB outperforms MI
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...demonstrated as a basis for constructing a multi-layered poly- r
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Further...pricing coe□cient with the units of bit/J, γi denotes the S
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Application Number: 10/814114 Assignments	Examiner Number: 80488 / TORRES, JUAN	
Filing or 371(c) Date: 03/30/2004 eDan	Group Art Unit: 2611	IFW Madras
Effective Date: 03/30/2004	Class/Subclass: 375/260.000	
Application Received: 04/01/2004	Lost Case: NO	
Pat. Num./Pub. Num: /20050223306	Interference Number:	
Issue Date: 00/00/0000	Unmatched Petition: NO	
Date of Abandonment: 00/00/0000	L&R Code: Secrecy Code:1	
Attorney Docket Number: 884.B70US1	Third Level Review: NO	Secrecy Order: NO
Status: 71 /RESPONSE TO NON-FINAL OFFICE ACTION ENTERED AND FORWARDED TO EXAMINER		Status Date: 07/27/2008
Confirmation Number: 5166	Oral Hearing: NO	

Title of Invention: MULTI-TONE COMMUNICATIONS APPARATUS, SYSTEMS, AND METHODS

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Inventor Information for 10/814114

Inventor Name	City	State/Country
FRANCA-NETO, LUIZ M.	SUNNYVALE	CALIFORNIA

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10118816	6714054	150	04/08/2002	AREA EFFICIENT WAVEFORM EVALUATION AND DC OFFSET CANCELLATION CIRCUITS	FRANCA-NETO, LUIZ
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